# New Biosensor Design Based on Photonic Crystal Core-shell Rods Defects for Detecting Glucose Concentration

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In this paper, an ultra compact photonic crystal (PhC) biosensor for detecting glucose concentration using resonant microcavity (RMC), sandwiched by two inline quasi-waveguides is investigated. The RMC is used as sensing region. It consisted of 7×7 core/shell (C/S) rod defects and 14 functionalized holes. The basic structure is formed by air holes arranged in hexagonal lattice in silicon (Si) background. The sensing mechanism of our biosensor is to detect the resonant wavelength shift, which is caused by the change of the refractive index (RI) of the shell layer and active holes filled with the analyte sample of glucose solution. The plane wave expansion (PWE) and finite difference time domain (FDTD) methods are chosen to analyze and simulate the performance of the suggested structure. The FDTD results reveal high sensitivity of 624.7904 nm/RIU with high linearity and quality factor. The presented sensor has a simple design and is easy to manufacture. In addition, the total size of the presented device is 92.65 μm$^2$ which is very small for nanotechnology based sensing.

**Keywords:** Photonic crystal, Glucose concentration, Biosensor, Resonant microcavity, Sensitivity.

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## 1. INTRODUCTION

Photonic crystal (PhC) biosensors have gained enormous interest of many researchers, due to their simplicity, high sensitivity and wide range of applications such as pressure [1, 2], temperature [3, 4], chemical gas [5], refractive index [6], biosensor to detect the glucose concentration in urine [7], cancer cell detection [8], virus [9], different blood constituents [10] and glucose concentration [11-13], etc. PhCs offer a promising prospect for ultra compact photonic devices and integrated circuits. They are used to reduce the components dimension to nanoscale range with ultra-low optical loss, this leads to a confinement of light within the structure. These materials with a periodic modulation in the dielectric constant, creates a frequency region where the light signal is not allowed to propagate inside the structure for both polarizations and all directions of the propagation. This forbidden frequency region is called photonic band gap (PBG), which makes PhC appropriate to control and manipulate the optical signal. By introducing different defects in PhC structure, allowed modes appear inside PBGs. This will give various applications such as, filters [14], logic gates [15] multiplexers and demultiplexers [16]. One of the most important components of PhC applications is optical sensor. In this context we have designed an optical PhC sensor to detect the glucose concentration. In this design PhC resonant microcavity is utilized as sensing region. The RMC are sandwiched by two inline waveguides. We have designed the proposed device by a hexagonal lattice of air holes in *Si* matrix. The plane wave expansion method is employed to calculate the diagram of dispersion and the sensing function is displayed using finite difference time domain. The design structure, sensing principle and the FDTD results are discussed in the following sections.

## 2. GLUCOSE BIOSENSOR DESIGN

In this paper, our goal is to design a new biosensor structure using two dimensional (2D) PhC to detect the glucose concentration with high sensitivity. For designing the suggested device, we employed 2D hexagonal lattice of air holes in silicon (Si) background. The radii of the pores are $r = 0.341a$, where $a$ is the distance between the two adjacent air holes. The refractive indexes of Si and air were considered as 3.4 and 1 respectively. The Si is a good candidate for PhC applications. The number of holes in $x$ and $z$ directions is 22 and 22, respectively. The total size of the structure is 92.65 μm$^2$, its dimension is very small which is suitable for use in integrated circuits.

The PBG of the fundamental structure without any defects calculated using PWE is depicted in Fig. 1. The basic structure has PBG for TM mode which is indicated by red region. As shown in Fig. 1, the normalized frequency is observed from 0.21722 ($a/\lambda$) to 0.31778 ($a/\lambda$), where $\lambda$ is the vacuum wavelength, which is sufficiently wide for sensing region.

Fig. 2 depicts the schematic structure of the designed glucose biosensor.

The suggested device consists of resonant microcavity and two horizontal inline quasi-waveguides. The inline quasi-waveguides are formed by omitting several holes in the $x$ direction. The RMC consists of 7×7 C/S rods and 14 functionalized holes. The C/S rod is made by Si rod covered by air shell layer. As illustrated in Fig. 2b, the parameters $rc$ and $rs$ denote the radii of the internal rod and the external shell-layer respectively.

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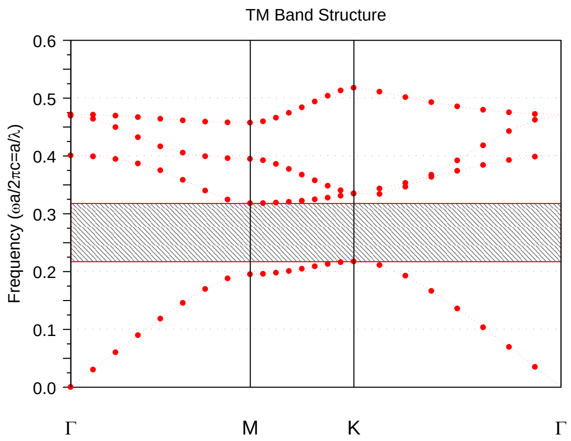


**Fig. 1** – Band structure of hexagonal PhC lattice of air holes in Si background for TM polarization

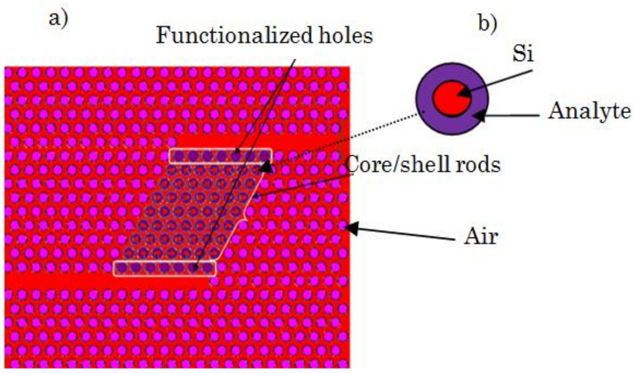


**Fig. 2** – The final sketch of the proposed PhC glucose biosensor (a), the diagrammatic presentation of the regular core/shell rod (b)

In the present work, we study the biosensor property of our suggested device. The designed biosensor is used to detect the glucose concentration over a range from 0 g/L to 90 g/L. The sensing principle is based on the change of the refractive index (RI) of the shell layer and the functionalized holes when the glucose concentration varies. In this study we have considered the inner and the outer radii of the C/S rods equal to $0.205a$ and $0.415a$ respectively. As illustrated in Fig. 2a, the radii of the functionalized holes, which are shown in gray color, are the same as radii of the shell layer ($r$s). The RI variation of glucose concentration from 0 to 90 g/L is calculated by [13]:

$$n = 0.00011889C + 1.33230545, \tag{1}$$

where $C$ is the glucose concentration in g/L.

The different glucose concentrations with known refractive indices, sensitivity and quality factor are displayed in Table 1.

A Gaussian input light signal with a central wavelength of 1.55 μm is launched into the input port of the inline quasi-waveguide. The power monitor is placed at the end of the output port. The sensing mechanism is to detect the resonance wavelength shift, which is caused by the change of RI of the 7×7 shell rods and 14 functionalized holes. A vital parameter in evaluating the performance of the designed sensor is the sensitivity ($S$) which is defined as:

$$S = \Delta\lambda / \Delta n, \tag{2}$$

where $\Delta\lambda$ is the change in the resonant wavelength and $\Delta n$ is the change in the RI. $S$ is measured in terms of nm/RIU and it should be as high as possible.

Another important parameter used to analyze the performance of the proposed structure is the quality factor ($Q$). $Q$ is defined as the ratio of stored energy loss and is given by:

$$Q = \lambda_0 / \Delta\lambda, \tag{3}$$

where $\lambda_0$ is the central wavelength of the transmission and $\Delta\lambda$ is the full width at half maximum of the output intensity.

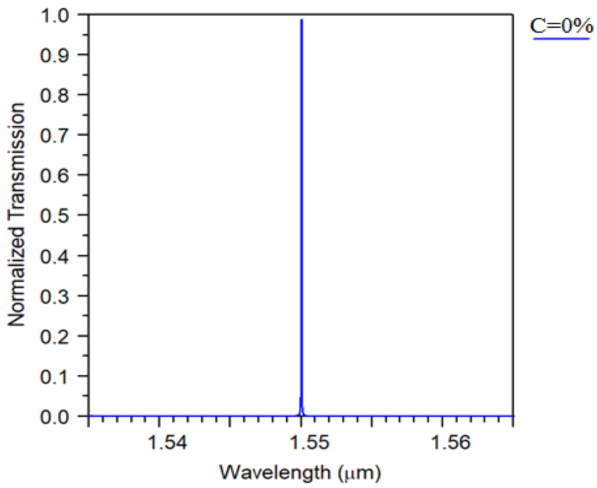


**Fig. 3** – Normalized transmission spectra of the proposed structure in the absence of glucose

Fig. 3 shows the transmission spectrum in the absence of glucose in the solution ($C$ = 0 %). The existence of a resonant peak at $\lambda$ = 1.55 mμ means that the inline quasi-waveguide can couple with the RMC, and this resonance possesses a high quality factor ($Q$).

In order to analyze the sensitivity of the designed structure, we change the RI of the C/S rods and active holes from 1.33230545 to 1.34300555. Fig. 4 depicts the normalized transmission obtained of the glucose concentration varying from 0 % to 90 %. It is revealed from this figure that the resonant mode is shifted due to higher frequencies when the RI increases. Every 15 g/L of $C$ variation results in 1.1 nm shift in the resonant mode. The transmission efficiency of the output spectra is more than 97.76 %.

In other to observe the effect of the outer radius ($r$s) of the shell layer on the resonant wavelength for $C$ = 0 %g/L, we vary the external radius from 0.41 $a$ to 0.419 $a$. Our results show that resonant mode is influenced by the change of $r$s. This mode is shifted to the lower wavelength (blue-shift) when the filled area increases. From Fig. 5, it can be noted that the graph obtained is varies quasi-linearly with respect to the variation of $r$s, when $r$s increases with a step of $0.001a$.

From the FDTD results, the designed structure sensitivity is equal to 624.7904 nm/RIU and the quality factor reaches 34505.712, in the RI range of 1.33230545 to 1.34300555. Furthermore, the dependence between

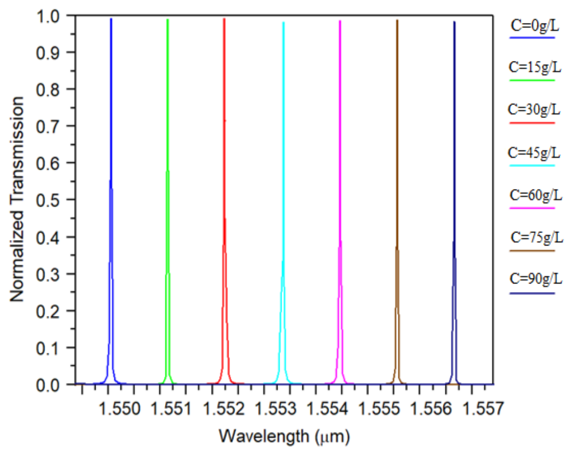


**Fig. 4** – Normalized transmission spectra of the proposed structure for different concentration of glucose

the RI variation and resonant wavelength shift is shown in Fig. 6. It revealed from this figure that the resonant wavelength varies linearly with the measurements of the different concentration of glucose.

The sensibility of the presented biosensor is better than that of some previous structures proposed in recent articles for detecting the glucose concentration [11, 17, 18]. The comparison of the existing sensing structures is displayed in Table 2. The total footprints of this proposed structure is 92.65 μm$^2$, its dimension is very small, it can be integrated easily with PC based devices and it offers high sensibility, high quality factor and good linearly, so we can utilize this type of devices as a glucose sensor.

**Table 1** – Refractive index, resonant wavelength, sensibility and quality factor with different glucose concentration

| *C* (g/L) | Refractive Index (RIU) | $\lambda_0$ (nm) | $\Delta\lambda$ (nm) | *S* (nm/RIU) | Quality factor (*Q*) |
|---|---|---|---|---|---|
| 0 | 1.33230545 | 1550.0 | | | 30418.329 |
| 15 | 1.3340888 | 1551.1 | 1.11422 | 624.7904 | 31050.726 |
| 30 | 1.33587215 | 1552.2 | 2.20238 | 617.4839 | 33897.342 |
| 45 | 1.3376555 | 1553.3 | 3.33591 | 623.5287 | 33324.337 |
| 60 | 1.33943885 | 1554.4 | 4.43148 | 621.2297 | 34505.712 |
| 75 | 1.3412222 | 1555.5 | 5.52858 | 620.0218 | 32135.634 |
| 90 | 1.34300555 | 1556.6 | 6.62548 | 619.1979 | 33022.014 |

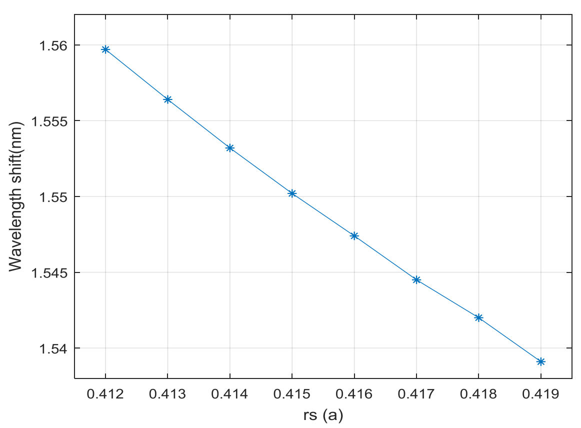


**Fig. 5** – The shift in the resonant wavelength as a function of the external radius (*rs*)

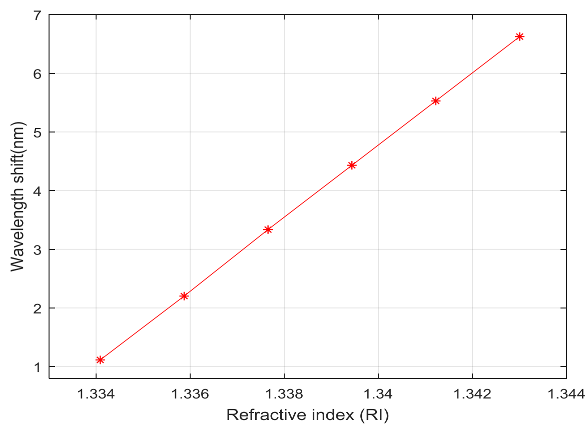


**Fig. 6** – Linear relationship between resonant wavelength and the RI

**Table 2** – Comparison of our results with some recent works

| Reference | Sensing structure | Quality factor | Sensibility (nm/RIU) |
|---|---|---|---|
| [11] | PhC microcavity | 549.2 | 422 |
| [17] | PhC ring slot cavity | $Q = 10^7$ | 160 |
| [18] | PhC ring shaped holes cavity-coupled waveguide | $1.11\times10^5$ | 462 |
| [19] | hexagonal nanocavity PhC resonator | 3860 | 544 |
| [20] | optofluidic-gas sensor using 2D PhC | 7070 | 575 |
| This work | PhC resonant microcavity | $3.4505\times10^4$ | 624.79 |

## 3. CONCLUSIONS

In this paper, an ultra compact optical biosensor based on PhC using core shell (C/S) rods and functionalized holes for detecting glucose concentration is investigated. This designed device is formed by hexagonal lattice of air holes in Si background. The sensing mechanism of our biosensor is to detect the resonant wavelength shift, when the analyte flows through these defect rods. The FDTD results show that the resonant mode shift is linearly proportional to the glucose concentration. Every 15 g/L of variation of glucose concentration results in 1.1 nm shift in the resonant peak. The suggested device provides high sensitivity and high quality factor compared with the reported studies. The total footprint of the designed structure is 92.65 μm$^2$, which is ultra compact and can be a promising platform to detect the glucose concentration.

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